BIOMECHANICAL VARIABLES OF THE YURCHENKO VAULT

By

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J19020

A Research Project submitted in partial fulfilment of the requirements of the University of Chester for the degree of M.Sc. Sports Sciences (Biomechanics)

September, 2015

Word Count: 5487

Declaration

No portion of the work referred to in this Research Project has been submitted in support of an application for another degree or qualification of this, or any other University or institute of learning.

The project was supervised by a member of academic staff, but is essentially the work of the author.

Signed …………………………………………………………….

Date ……………………………………………………………

Abstract

The first aim was to identify the key temporal and spatial biomechanical variables of the Yurchenko vault from the deterministic model in relation to judges' score. Secondly, to identify differences between international and national level gymnasts of temporal and spatial biomechanical variables identified in the deterministic model. Twenty female gymnasts, divided into national or international level gymnasts, were filmed using two 300 Hz cameras placed perpendicular to the movement. The data were manually digitised using an 18-point model and filtered using a Butterworth's low pass filter of 6 Hz. Pearson's correlation coefficient was used to identify the relationship between biomechanical variables and judges' score. Independent t-tests were used to compare national to international level gymnasts. A significant correlation to judges' score was found for body angle at vault touchdown (p = 0.002) and post-flight time (p = 0.027). Furthermore, a significant difference (p < 0.001) for five out of 31 variables were found between national and international level gymnasts which included; pre-flight time, post-flight time, body angle at vault touchdown, shoulder angle at vault touchdown, and vertical velocity at vault take-off. In conclusion, to perform a high scoring vault, it is important to minimise the body angle at vault touchdown and maximise the post-flight time. Finally, international level gymnasts' exhibited a shorter pre-flight time and a lower body angle at vault touchdown, whereas national level gymnasts demonstrated a lower shoulder angle at vault touchdown, a lower vertical velocity at vault take-off and a shorter post-flight time.

Acknowledgements

I would like to express my deepest gratitude to the following people:

- My supervisor Dr. Grace Smith for her continual support and guidance throughout this project,
- Dr. Claire Williams, who has provided external assistance and guidance with aspects of my work,
- My family and friends who have supported me through an extremely difficult year,
- And British Gymnastics and the English Institute of Sport for financial support.

Contents **Page**

List of Figures

List of Tables

Chapter 1. Introduction

In Gymnastics, the vault involves execution of a single element, which can be influenced by several variables (Farana & Vaverka, 2012), and is evaluated by a panel of judges using a performance-based criteria recognised as the Code of Points (CoP) (Fédération Internationale de Gymnastique, 2013b). The vault can be split into several phases (Figure 1). Previous research has focused on either single phases of the vault (Penitente et al., 2007; Velickovic, Petkovic, & Petkovic, 2011); pre-flight phases (Koh & Jennings, 2007; Yeadon, King, & Sprigings, 1998), or post-flight phases (Takei, 1992; Yeadon, Jackson, & Hiley, 2014). This study will focus on all phases of the vault.

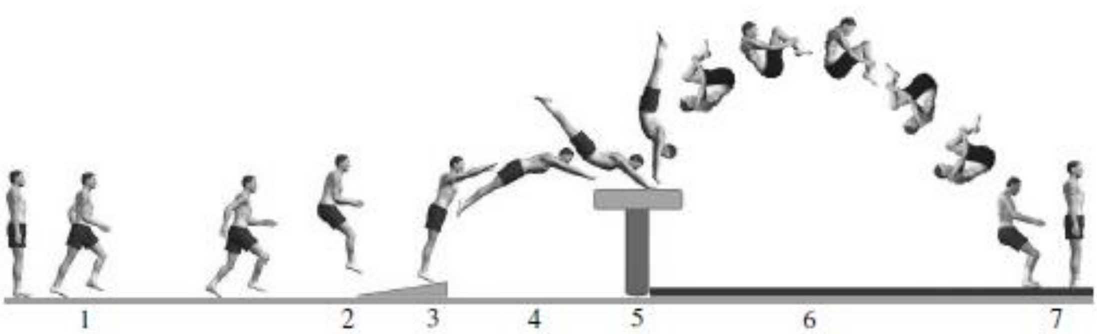

Figure 1: Seven vault phases; 1) approach, 2) hurdle onto springboard, 3) springboard support, 4) pre-flight, 5) vault support, 6) post-flight and 7) landing, from (Atiković & Smajlović, 2011). Phase definitions can be found in Appendix A.

There are five different vault entries that a gymnast can perform (Appendix B). Studies have previously focused on providing biomechanical variables of an individual vault entry (Brehmer & Naundorf, 2014; Farana, Uchytil, Zahradnik, & Jandacka, 2015; Farana, Uchytil, Zahradník, & Jandačka, 2013; Takei, 2007; Yeadon et al., 1998) or comparing different vault entries (Farana, Uchytil, Jandacka, Zahradnik, & Vaverka, 2012; Farana, Uchytil, Zahradník, Jandacka, &

Vaverka, 2014; Motoshima & Maeda, 2015). However, Farana et al. (2015) stated it is necessary to broaden the research using different vault entries, under the conditions of a real competition using a wider sample size of top-level gymnasts, to allow a more representative sample of the population and to produce more significant results. This study will focus on providing biomechanical variables of the Yurchenko vault during competitions.

Deterministic models have been used to avoid subjectively selecting variables and to guide analysis between mechanical variables and judges' score (Chow & Knudson, 2011; Takei, 1998), such as the one demonstrated in Figure 2. Correlation analysis has provided important performance variables in gymnastic vaulting that are significantly associated with judges' score. A high correlation between approach running velocity (6.80 m/s to 7.70 m/s) and performance score has been found (Bradshaw & Sparrow, 2001; Kashuba, Khmelnitska, & Krupenya, 2012; Van der Eb et al., 2012).

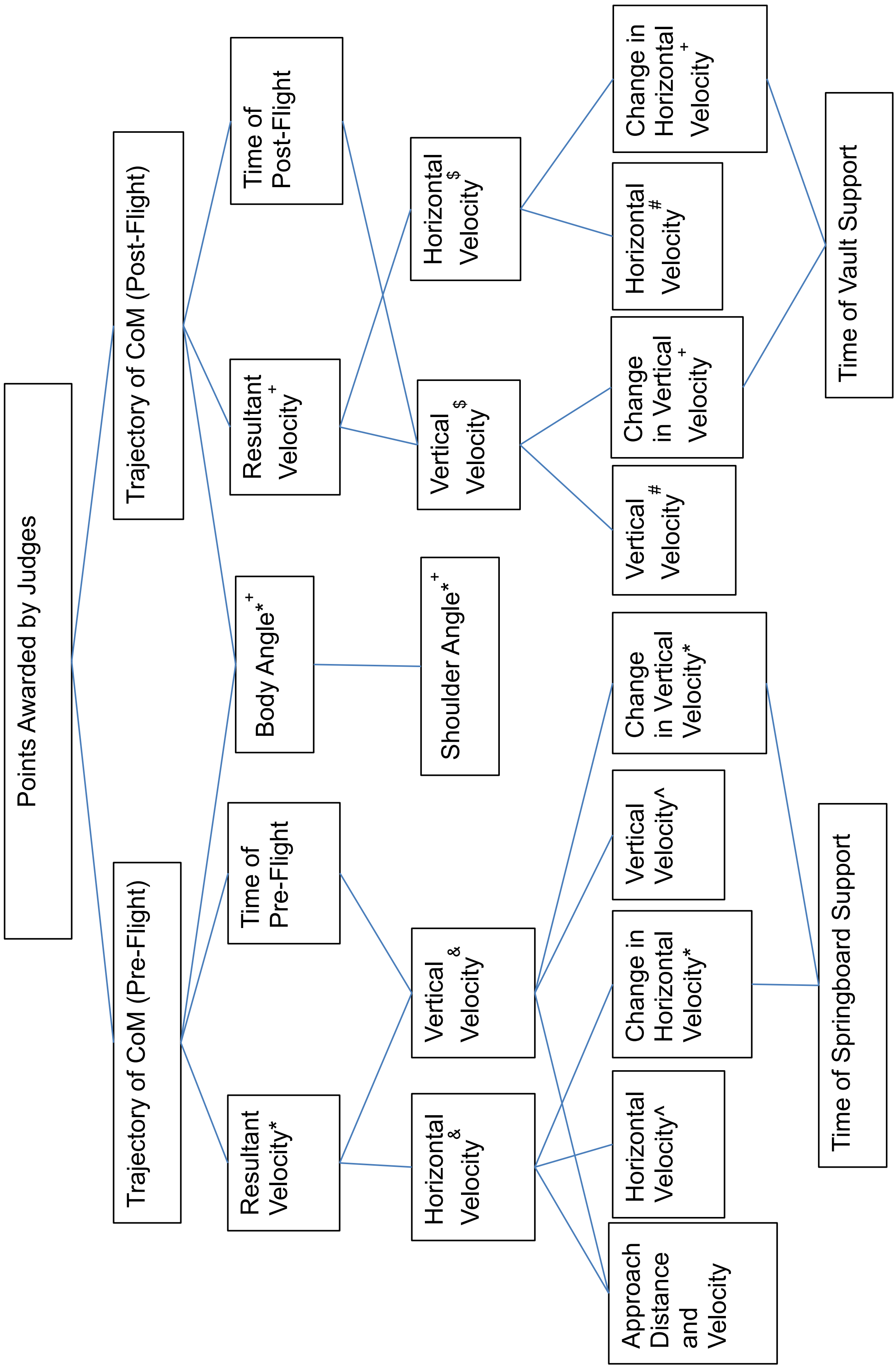

Figure 2: Deterministic Model of Vault, adapted from Takei (1998), Hay and Reid (1988), Penitente et al. (2009) and Farana and Vaverka (2012), * Springboard touchdown and take-off; ^ Springboard touchdown; [&] Springboard take-off; [+] Vault touchdown and take-off; [#] Vault touchdown; [$] Vault take-off.

Increasing approach velocity has resulted in higher velocity at springboard take-off, an increase in pre- and post-flight times, and a decrease in springboard and vault contact times (Bradshaw & Sparrow, 2001; Farana et al., 2013). Vertical velocity at vault take-off has been reported to explain 49% of score variability and is significantly correlated with judges' score (Farana et al., 2013). Farana and Vaverka (2012) and Farana et al. (2013) highlighted the importance of vault contact time and post-flight time, explaining 50% and 38% variability of judges' score respectively. These results support Bradshaw (2004), who found reduced springboard and vault contact times encourage the gymnast to transform the approach running velocity into a longer post-flight time. An increase in horizontal (18%), vertical (4%) and resultant (4%) velocity was found for springboard rear foot placement compared to middle foot placement (Coventry, Sands, & Smith, 2006).

Another factor is body angle (Figure 3A and 3B) at key positions. Body angle at springboard touchdown is reported around 60° (Penitente, 2014; Penitente et al., 2007), whereas body angle at springboard take-off increases to 96° to maximise the upward vertical velocity (Penitente, 2014). A body angle of 43° at vault touchdown has been highlighted to enhance post-flight time (Koh & Jennings, 2007). Body angle at vault touchdown has been correlated with judges' score for a Handspring Hetch vault (Takei, Blucker, Nohara, & Yamashita, 2000; Yeadon et al., 1998), but was not correlated with judges' score for Handspring compulsory vault in 1988 (Takei, 1992). However, a difference between body angle at vault touchdown, for high and low scoring Olympic vaults has been found (Takei, Blucker, Dunn, Myers, & Fortney, 1996).

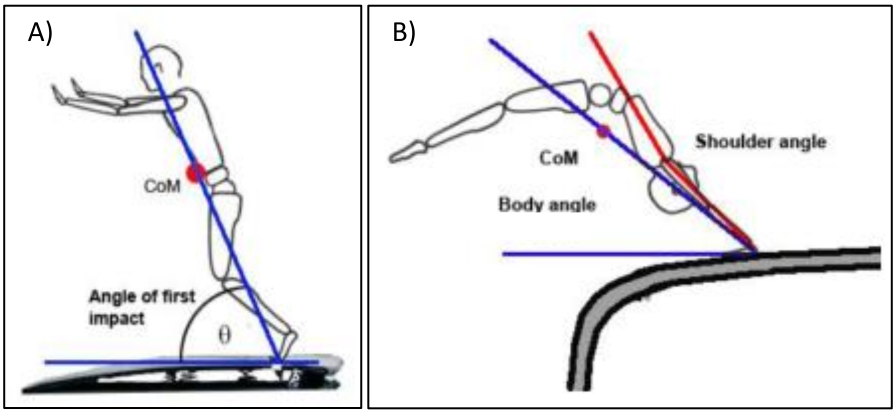

Figure 3: A) Springboard body angle defined as the horizontal line and the line passing through the Centre of Mass (CoM) and the toes (Penitente et al., 2007); B) Vault body angle (blue) defined as the angle the CoM makes with the point of impact (fingertips) and the horizontal line and shoulder angle (red) was defined as the angle passing between the arm and mid trunk (Uzunov, 2010).

A shoulder angle (Figure 3B) between 160° to 170° at vault touchdown is also needed (Koh & Jennings, 2007; Uzunov, 2010). Koh, Jennings, Elliott, and Lloyd (2003) optimised a Yurchenko vault and found shoulder angle should be between 173° to 187°. To achieve a larger shoulder angle at vault touchdown, Elliott and Mitchell (1991) advised a shoulder angle of 161° at springboard take-off is necessary, which transferred into 166° at vault touchdown. More recently, Penitente (2014) found shoulder angle at springboard take-off was 198°, although shoulder angle at vault touchdown was not reported, it could be suggested that a larger shoulder angle would be transferred onto vault touchdown.

Penitente (2014) recently focused on the Yurchenko vault and used a deterministic model to compare biomechanical variables to judges' score. It found; horizontal velocity at springboard touchdown, springboard contact time and pre-flight time were significantly correlated with judges' score. Twelve female participants completed the vault at a 2006 competition, using 100 Hz cameras for data collection. The data processing methods used within this study were not rigorous. Identification of frames pre- and post- key events were not used when digitising and the filtering process was based on a reference and not conducted on the current data. Furthermore, Penitente (2014) did not have access to body mass and used the 3D location of CoM using Dempster's anthropometric parameters 1995. The study also found that there were no significant differences found between two different Yurchenko vaults. Multiple t-tests were used, but the probability value was not adjusted for the number of variables, therefore increasing the chance of a type I error. The main limitation was the data analysed within this study was collected from a 2006 competition.

More recently, Farana et al. (2015) focuses specifically on Tsukahara vaults. This study indicated that it used 15 male participants; yet the results stated that only eight vaults were used. This reduces the power and external validity of the study. The results highlighted a significant correlation to judges' score was found for; peak height of CoM, vertical velocity at vault take-off and post-flight time. Similar to Penitente (2014), the data processing method were questionable. The frame rate of data collection was 50 Hz, which could produce inaccurate data due to the vault being a fast explosive movement; collecting data at a low sampling rate could miss important events like the frame of touchdown and take-off on the vault.

Previous research has also compared technique differences between high and low scoring vaults. Takei (1991), Takei et al. (1996) and Takei, Dunn, and Blucker (2003) compared techniques of high and low scoring vaults at the 1988, 1992 and 2000 Olympic Games. They found higher scoring vaults exhibited significantly greater horizontal velocity during the hurdle and pre-flight phases, a significantly greater change in vertical velocity during vault contact and a significant difference between body angle at vault touchdown and take-off. Takei, Dunn, Blucker, Nohara, and Yamashita (2000) also found a greater post-flight time for higher scoring vaults at the 1995 World Championships. Similarly the same technique differences were found between Olympic and American Gymnasts (Takei & Kim, 1990). The results provide insights for improvement of performance of national level gymnasts. American gymnasts need to focus on; improving approach velocity, maintaining velocity during pre-flight and transferring horizontal to vertical velocity on the vault, which subsequently should result in a longer post-flight time. However, these studies were completed prior to the equipment change in 2001 and prior to the change in the CoP in 2013 (Fédération Internationale de Gymnastique, 2013b).

Research during competition focusing on the Yurchenko vault is limited (Kwon, Fortney, & Shin, 1990; Nelson, Gross, & Street, 1985; Penitente, 2014; Penitente et al., 2009; Penitente et al., 2007), as research was generally completed prior to the change in vaulting equipment. Research has also been conducted within the training environment (Bradshaw & Sparrow, 2001; Elliott & Mitchell, 1991; Hedbávný & Kalichová, 2015; Kashuba et al., 2012). Studies have used small sample sizes (4), Farana et al. (2013) suggested using larger sample sizes, however Irwin and Kerwin (2009) stated small sample sizes are indicative when undertaking research within an elite competition environment. Majority research have used 8 to 18 year olds, Brehmer and Naundorf (2011) found differences between age groups for vault running velocity, therefore data from under 18's cannot be applied to gymnasts over 18. There are limited reported physical characteristics of gymnasts included in research; this can lead to misinterpretation of the findings as the exact level of gymnasts is rarely defined.

The vault is an explosive short movement; therefore using a low sampling rate could produce inaccurate data. Some research used 50 Hz to 60 Hz sampling rate (Brehmer & Naundorf, 2014; Farana et al., 2015; Farana et al., 2013; Farana et al., 2014; Farana & Vaverka, 2012; Kashuba et al., 2012; Yeadon et al., 1998), whilst other studies used sampling rates between 100 Hz and 250 Hz (Hedbávný & Kalichová, 2015; Penitente, 2014; Penitente et al., 2009; Penitente et al., 2007; Takei, 2007; Van der Eb et al., 2012). One study used a 50 Hz panning camera to focus on the approach of the vault, but due to the springboard take-off to landing phase being short in duration, an additional camera sampling at 300 Hz was placed to focus on the springboard to landing phase (Heinen, Jeraj, Thoeren, & Vinken, 2011).

To improve the analysis accuracy or to increase the relative image size, using two-dimensional analysis allows multiple cameras to be used (Prassas, Kwon, & Sands, 2006). For example, Nelson et al. (1985) used two 100 Hz cameras, both perpendicular to the movement of the gymnast, with the vault serving as a common object. No other study uses this methodology. Other studies (Takei, Blucker, et al., 2000; Takei et al., 2003) have used three-dimensional camera placement by having a 90° axis between cameras, but using lower sampling rates. Two-dimensional analysis is deemed more suitable for elite competition as it has fewer restrictions (Prassas et al., 2006), for example the cameras do not have to have a perpendicular axis and multiple cameras can be used to increase image size and improve accuracy of analysis.

Previous research was generally completed prior to the change in equipment (Bradshaw, Hume, Calton, & Aisbett, 2010), biomechanical data is yet to be established (Farana & Vaverka, 2012). Therefore the first aim is to identify the key temporal and spatial biomechanical variables of the Yurchenko vault from the deterministic model in relation to judges' score. The second aim is to identify differences between national and international level gymnasts of temporal and spatial biomechanical variables identified in the deterministic model.

The research hypotheses are; 1) there is a significant correlation between temporal and spatial biomechanical variables identified in the deterministic model and judges' score and 2) there is a significant difference between national and international level gymnasts for temporal and spatial biomechanical variables identified in the deterministic model.

Chapter 2. Methodology

2.1 Participants

Following written informed consent (Appendix C), 20 female gymnasts participated in this study as part of their standard competition regime. All gymnasts had extensive experience in vaulting and competed at either Glasgow World Cup 2014 or Artistic Gymnastics British Championships 2015 (Table 1). Sample size was calculated at 10 per group using a large effect size of 1.2 from Hopkins (2002), power 0.8 and alpha 0.05. All gymnasts performed a Yurchenko vault with a difficulty value of greater than 5.00 according to the CoP 2013-2016 (Fédération Internationale de Gymnastique, 2013b). The gymnasts were divided into either national or international level gymnasts. International level gymnasts were defined as those that have competed at World Championships, European Championships and World Cup events. National level gymnasts were eligible to compete at the British Championships 2015, but have not achieved the standard required to compete for Great Britain or Northern Ireland at international events. Vaults were excluded if the judges' total score was below 13.500. The University of Chester Ethics Committee and British Gymnastics approved the biomechanical investigations, which did not involve any invasive procedures during competition. In order to remain unobtrusive no markers were attached to the gymnasts included in this research. Ethical approval was granted by Dr. Stephen Fallows (Chair, Faculty Research Ethics Committee) on 9th June 2015 (Appendix D).

Table 1: Physical characteristics and personal bests for gymnasts

	National	International
Age (yrs)	19 ± 1	20 ± 4
Height (cm)	153.98 ± 7.81	151.96 ± 7.58
Weight (kg)	50.4 ± 7.0	48.3 ± 8.0
Personal Best	14.686 ± 0.400	14.905 ± 0.120

2.2 Design

This study was an observational study with two independent groups; national and international level gymnasts. The dependent variable was total judges' score. The following independent variables were measured during critical vault phases (Appendix A); Horizontal and vertical velocity of CoM (m/s), time (s), body angle (°), shoulder angle (°) and distance (m). The full list of independent variables can be seen in Appendix E.

2.3 Procedure

Two 300 Hz video cameras (EX-F1, Casio, Japan) were placed in different locations, perpendicular to the running direction, in accordance with previous research (Cavanagh et al., 1985; Mero & Komi, 1985). One camera focused on the springboard to vault phase and the other focused on the vault to landing phase. Each video camera provided a 6.00 m field of view, a shutter speed of 1/1000 s, and was manually focused (Figure 4A to 4C). A 1.21 m x 1.21 m calibration object was placed in both cameras field of view. One panning digital video camera recorder (HC-W850, Panasonic, Japan) was used, sampling at a frequency of 50 Hz for approach.

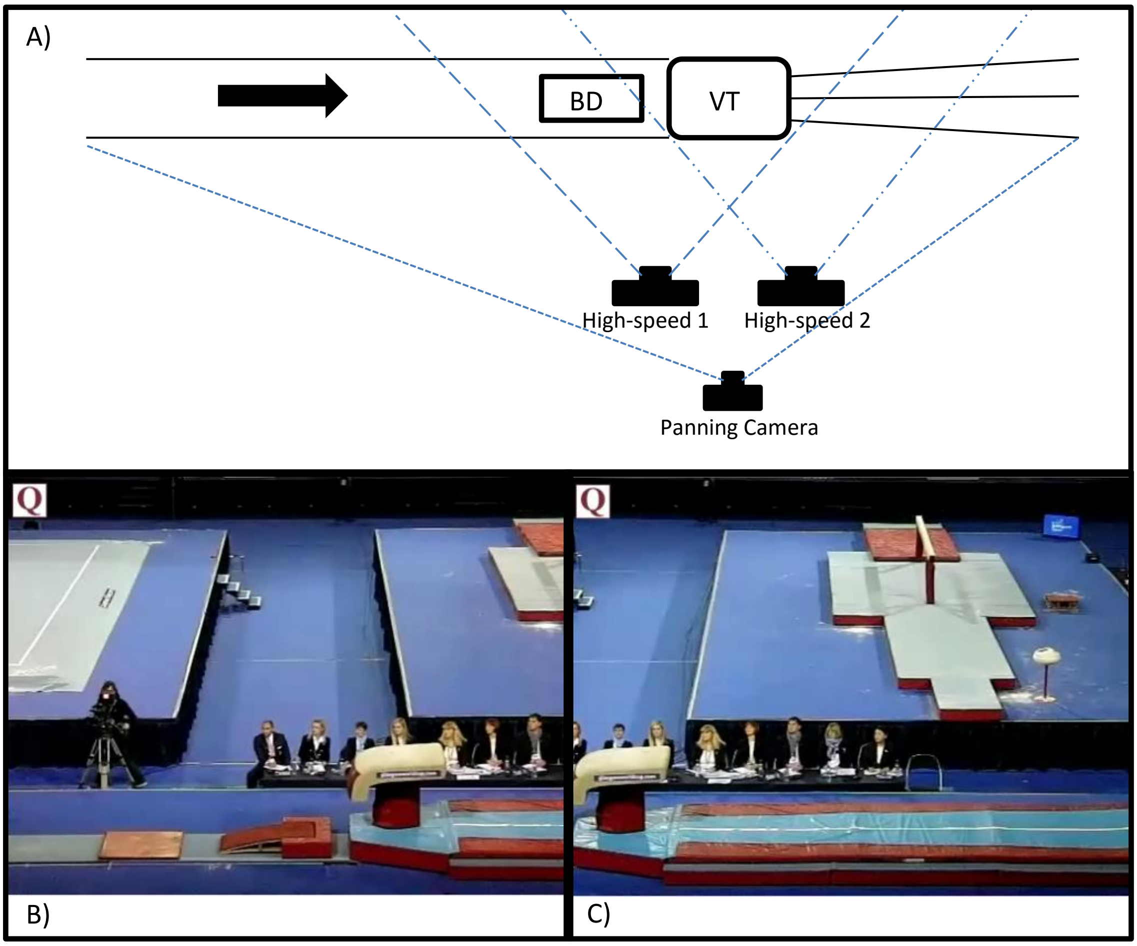

Figure 4: A) illustration of vault capture area depicting the direction of vault and positioning of biomechanical equipment (BD, Springboard; VT, Vault), B) camera view from high-speed camera 1, and C) camera view from high-speed camera 2.

2.4 Data Analysis

An 18-point model was used to manually digitise the high-speed video data in Quintic Biomechanics (Quintic Consultancy Ltd, 9.03 Version 26). The 18-point model consisted of the shoulder, hip, elbow, wrist, tip of the finger, knee, ankle, and toe on each side of the body, and top of the head and base of the neck. The CoM was determined in accordance with de Leva (1996) using the 18-point model. Each trial was digitised 20 frames pre- first contact of last step and 20 frames post landing. Each trial was digitised twice and the average of each trial was used.

All trajectories were filtered using a Butterworth's low pass filter with a cut-off frequency of 6 Hz. This cut-off frequency was decided using residual analysis, as described by Winter (2009), and is in accordance with previous research (Farana & Vaverka, 2012; Penitente, 2014). All digitised data were exported from Quintic Biomechanics and processed through Microsoft Office Excel 2010. The biomechanical variables were calculated on the basis of the exported x and y coordinates.

2.5 Statistical Analysis

Standard statistical methods were used for the calculations of means and standard deviations of each biomechanical variable. Normal distribution of the data was verified by the Shapiro-Wilk test ($p > 0.05$) and homogeneity of variance was verified by the Levenne test ($p > 0.05$). Normality was 80% plausible. Both statistical tests used are robust to moderate violations in normality assumptions (Ntoumanis, 2003). Pearson's correlation was used to find significant correlations between biomechanical variables and judges' score and significance was set at $p < 0.05$. Coefficient of determination (R^2) was also calculated. For comparison of national and international level gymnasts, independent t-tests were used. Bonferroni adjustment was used for the 31 variables entered, resulting in significance defined as $p < 0.002$. This level was used to control the increase in type I error rate due to performing multiple t-tests.

Chapter 3. Results

Average total judges' score was 14.038 ± 0.236 for national level gymnasts and 14.527 ± 0.437 for international level gymnasts.

Although a total of 31 biomechanical variables were examined, the results from Pearson's correlation found a significant relationship between two variables and total judges' score. A significant positive correlation was found for post-flight time (r = 0.494, n = 20, p = 0.027) and a significant negative correlation for body angle at vault touchdown (r = -0.640, n = 20, p = 0.002). Therefore hypothesis 1 is accepted. R^2 indicated that post-flight time and body angle at vault touchdown explains 24% and 41% of the total variability of the judges' total score. If a variable represents more than 10% of total variability it is deemed important (Takei, 2007).

Means, standard deviations and t values for time, distance, velocity, and angle variables are presented (Tables 2 – 5) and demonstrate significant differences between national and international level gymnasts. Therefore hypothesis 2 is accepted. Findings displayed in Table 2 highlight international level gymnasts have a significantly shorter pre-flight time (t (18) = 3.745, p = 0.001) and a significantly longer post-flight time (t (18) = -5.482, p < 0.001).

Table 2: Comparison of time at vault phases for national and international gymnasts (Mean ± STD)

Variable	National	International	*t*
Time (s)			
On Springboard	0.141 ± 0.01	0.139 ± 0.01	0.750
Pre-flight	0.143 ± 0.02	0.103 ± 0.02	3.745*
On Vault	0.186 ± 0.03	0.194 ± 0.01	-0.920
Post-Flight	0.781 ± 0.04	0.871 ± 0.03	-5.482*

* $p < 0.001$

No significant differences were found between national and international level gymnasts were found for distance variables (Table 3).

Table 3: Comparison of distance at vault phases for national and international gymnasts (Mean ± STD)

Variable	National	International	*t*
Distance (m)			
Round-off	2.74 ± 0.28	2.98 ± 0.37	-1.638
Springboard Foot	0.34 ± 0.09	0.34 ± 0.08	-0.081
Between Springboard and Vault	0.55 ± 0.16	0.48 ± 0.12	1.079
Vault Hand	0.59 ± 0.12	0.71 ± 0.17	-1.746
Landing	2.01 ± 0.21	2.00 ± 0.30	0.077

In addition, international level gymnasts also have a significantly higher vertical velocity at vault take-off (t (18) = -5.103, $p < 0.001$, Table 4). At vault touchdown, national level gymnasts have a lower vertical velocity which is further reduced at vault take-off, but international level gymnasts have a higher vertical velocity at vault touchdown and maintain the velocity at vault take-off.

Table 4: Comparison of horizontal and vertical velocity at vault phases for National and International gymnasts (Mean ± STD)

Variable	National	International	*t*
Horizontal Velocity (m/s)			
Approach	5.98 ± 0.59	6.27 ± 0.58	-1.126
Springboard touchdown	5.09 ± 0.49	5.68 ± 0.57	-2.517
Springboard take-off	3.78 ± 0.50	3.98 ± 0.32	-1.04
Change Springboard touchdown to take-off	-1.31 ± 0.34	-1.70 ± 0.34	2.618
Vault touchdown	3.70 ± 0.59	3.91 ± 0.37	-0.940
Vault take-off	2.86 ± 0.44	2.86 ± 0.41	0.024
Change Vault touchdown to take-off	-0.84 ± 0.56	-1.05 ± 0.37	0.995
Vertical Velocity (m/s)			
Approach	0.98 ± 0.22	0.88 ± 0.29	0.912
Springboard touchdown	-0.16 ± 0.12	-0.15 ± 0.17	-0.250
Springboard take-off	3.76 ± 0.47	3.95 ± 0.36	-1.023
Change Springboard touchdown to take-off	3.92 ± 0.52	4.09 ± 0.43	-0.816
Vault touchdown	2.60 ± 0.31	2.96 ± 0.44	-2.138
Vault take-off	2.21 ± 0.39	3.02 ± 0.30	-5.103*
Change Vault touchdown to take-off	-0.38 ± 0.46	0.06 ± 0.25	-2.681

* $p < 0.001$

Body and shoulder angle at vault touchdown also differed significantly between national and international level gymnasts (t (18) = 4.090, p = 0.001; t (18) = -4.242, p < 0.001, Table 5), with international level gymnasts having a smaller body angle and a larger shoulder angle at vault touchdown.

Table 5: Comparison of body and shoulder angle at vault phases for National and International gymnasts (Mean ± STD)

Variable	National	International	*t*
Body Angle (°)			
Springboard Touchdown	58 ± 3	55 ± 4	1.649
Springboard Take-off	102 ± 3	100 ± 2	1.459
Vault Touchdown	28 ± 6	18 ± 5	4.090*
Vault Take-off	85 ± 5	84 ± 6	0.380
Shoulder Angle (°)			
Springboard Touchdown	130 ± 12	124 ± 15	1.057
Springboard Take-off	172 ± 16	173 ± 17	-0.118
Vault Touchdown	158 ± 30	202 ± 14	-4.242*
Vault Take-off	153 ± 15	155 ± 13	-0.201

* $p < 0.001$

Chapter 4. Discussion

The first aim of the study was to identify the key temporal and spatial biomechanical variables of the Yurchenko vault from the deterministic model in relation to judges' score. The second aim was to identify differences between national and international level gymnasts of temporal and spatial biomechanical variables identified in the deterministic model. Both research hypotheses are accepted; there is a significant correlation between temporal and spatial biomechanical variables identified in the deterministic model and judges' score, and there is a significant difference between national and international level gymnasts for temporal and spatial biomechanical variables identified in the deterministic model.

4.1 Pre-flight time

In this study pre-flight time was not significantly related to judges' score, which is supported by previous research (Farana et al., 2015; Farana et al., 2013; Takei, Blucker, et al., 2000; Takei & Kim, 1990). Takei (1998) reported, for Handspring vaults, a shorter pre-flight time was correlated to higher judges' score. High scoring Olympic vaults had a significantly lower pre-flight time compared to low scoring Olympic vaults (Takei et al., 1996). Conversely, other studies (Takei, 1991; Takei et al., 2003) found no significant difference between high and low scoring vaults for pre-flight time and similarly Takei and Kim (1990) also found no significant difference between Olympic and American gymnasts for pre-flight times, but did not state why no differences was observed. However, results of the current study found a significant difference between national (0.143s ± 0.02) and international (0.103s ± 0.02) level gymnasts pre-flight times.

Longer pre-flight times increase post-flight deductions (Penitente, 2014), where 39% of variance in post-flight deductions were explained by the duration of pre-flight. Therefore having shorter pre-flight times should increase judges' score. Pre-flight times over the past decade have decreased. Gymnasts should be encouraged to generate more rotation to reach the vault earlier and avoid point deductions in the post-flight phase (Penitente, 2014). To reduce pre-flight time, it is advised gymnasts should have a larger shoulder angle at springboard take-off. If a gymnast does not have a large shoulder angle, this could increase pre-flight time and reduce the conversion of horizontal to vertical velocity (Uzunov, 2010).

4.2 Shoulder angle at vault touchdown

Shoulder angle at vault touchdown was not correlated with judges' score and no previous studies have attempted to correlate shoulder angle with judges' score. Despite finding no correlation to judges' score, the current study did find shoulder angle at vault touchdown was significantly different between national (158° ± 30°) and international (202° ± 14°) level gymnasts. No other studies have compared shoulder angles for high and low scoring vaults.

For higher vertical velocities, the shoulders need an angle greater than 190°, defined as hyper-flexion, Yeadon et al. (2014) suggests gymnasts need to improve shoulder strength to allow for control of movement through this extended shoulder range. International level gymnasts achieved a shoulder angle of 202°, which suggests, having a hyper-flexed shoulder angle could be due to producing a higher vertical velocity at vault take-off. This large shoulder angle allows the gymnasts to achieve the correct blocking technique which transforms the horizontal velocity to vertical velocity required when leaving the vault (Uzunov, 2010). Blocking is defined as the pushing off the vault with the arms and shoulders (Takei, 1991).

Shoulder angle has been correlated to the rotation potential of the vault (Yeadon et al., 1998). Rotation potential was defined as how much backwards rotation was achieved. A small shoulder angle would increase the backwards rotation and have little change in velocity of the CoM. Yeadon et al. (1998) suggested a greater shoulder angle at vault touchdown would create higher CoM location at vault take-off and a greater change in velocity on the vault. Koh et al. (2003) created an optimised vault and suggested higher scoring vault is associated with a greater shoulder flexion (< 174°).

In this study, a larger shoulder angle is achieved by the international level gymnasts, which could also be due to achieving a smaller body angle at vault touchdown. Having a smaller body angle at vault touchdown forces the gymnast to hyper-flex the shoulders in order to reach the vault (Koh & Sujae, 2005). When a gymnast has a low body angle at vault touchdown and they do not hyper-flex the shoulders, they would be unable to complete the vault contact phase and collapse during the pre-flight phase. National level gymnasts have a higher body angle at vault touchdown, meaning the shoulders do not need to hyper-flex in order to contact the vault. Hence the smaller shoulder angle of national level gymnasts.

4.3 Body angle at vault touchdown

A significant negative correlation was found between body angle at vault touchdown and judges' score, explaining 41% of total variability of judges' score. This relationship suggests a smaller body angle at vault touchdown increases judges' score. Takei, Blucker, et al. (2000) and Yeadon et al. (1998) also found a significant correlation to judges' score and body angle at vault touchdown. However Takei (1991) and Takei (1992) did not find any correlation between body angle at vault touchdown and judges' score. For Yurchenko vaults, Kwon et al. (1990) also found no significant correlation to judges' score for body angle at vault touchdown.

A significant difference between national (28° ± 6°) and international (18° ± 5°) level gymnasts for body angle at vault touchdown has also been found in this study. Concurring with this study's findings, Takei et al. (1996) and Takei, Dunn, et al. (2000) also found significant differences between high and low scoring vaults for body angle at vault touchdown. Conversely, studies have also found no significant difference between high and low scoring vaults (Takei, 1991; Takei et al., 1996; Takei et al., 2003), and between Olympic and American gymnasts (Takei & Kim, 1990).

International level gymnasts have a low body angle of 18° compared to 28° for national level gymnasts. A low body angle below 30° above the horizontal, could be associated with a greater vertical velocity at vault take-off (Takei et al., 1996). Koh and Sujae (2005) also found gymnasts produce a low body angle between 20° and 25° but it was suggested a higher body angle at vault touchdown is necessary to increase the CoM and has implications on post-flight time. Koh et al. (2003) and Koh and Jennings (2007) optimised a Yurchenko vault and found the optimum body angle at vault touchdown was between 32° and 43°. This higher body angle tends to facilitate the generation of angular momentum and is associated with shorter vault contact times (Uzunov, 2010), which also increases vertical velocity at vault take-off and subsequently increases post-flight time and judges' score (Koh et al., 2003). Further research is needed to clarify whether a higher or lower body angle is necessary for higher scoring vaults.

4.4 Vertical velocity at vault take-off

Vertical velocity at vault take-off was not significantly correlated to judges' score, which is supported by Farana and Vaverka (2012). Conversely, other studies have correlated a higher judges' score with greater vertical velocity at vault take-off (Farana et al., 2015; Farana et al., 2013; Takei, 1992, 1998; Takei, Blucker, et al., 2000; Takei & Kim, 1990). By having a greater vertical velocity at vault take-off, it ensures a longer post flight time, with a larger distance and height of the post-flight phase (Takei & Kim, 1990).

In the present study, international (3.02 m/s ± 0.30) level gymnasts have a significantly greater vertical velocity at vault take-off compared to national (2.21 m/s ± 0.39) level gymnasts. This corresponds to previous research on high and low scoring vaults, where higher scoring vaults achieve greater vertical velocity at vault take-off (Takei, 1991; Takei et al., 1996; Takei, Blucker, et al., 2000; Takei et al., 2003; Takei, Dunn, et al., 2000). Research on Olympic gymnasts found they also achieve a significantly higher vertical velocity (2.98 m/s ± 0.35) at vault take-off when compared to American gymnasts (2.69 m/s ± 0.28) (Takei & Kim, 1990). Vertical velocity at vault take-off is also significantly different between vault types, Motoshima and Maeda (2015) found Handspring Kasamatsu vaults had significantly higher vertical velocity compared to Handspring Tsukahara vaults.

Vertical velocity at vault take-off is important in producing longer post-flight times (Čuk & Karacsony, 2004), to support this Takei (1992) found a significant correlation between large vertical velocity at vault take-off and a longer post-flight time (r = 0.97, p <0.01). To achieve a large vertical velocity, a large horizontal velocity achieved throughout the previous stages of the vault is needed to transfer into vertical velocity at vault take-off, which subsequently creates a longer post-flight time and distance (Takei, 1992). The correct positioning of the arms and shoulders during the blocking phase at vault touchdown is essential to achieve the large vertical velocity at vault take-off.

4.5 Post-flight time

A significant positive correlation was found between post-flight time and judges' total score; this concurs with previous research (Farana et al., 2015; Farana et al., 2013; Farana & Vaverka, 2012; Kwon et al., 1990; Takei, 1991, 1992; Takei, Blucker, et al., 2000). Post-flight time explains 24% of the variability of the score, which suggests a longer post-flight time increases judges' score.

Increasing post-flight time enables gymnasts to complete complex movements whilst airborne, thus increasing the difficulty and potential to increase score (Bradshaw et al., 2010), and also enables the gymnast to prepare for landing (Takei, 1991).

Overall post-flight time is determined by a number of factors prior to vault take-off. A longer pre-flight time is likely to reduce post-flight time. This could be due to not hyper-extending the shoulders prior to vault touchdown, which could be caused by having a high body angle at vault touchdown, without the correct blocking technique, there is a reduction in the transformation of horizontal to vertical velocity and consequently less height off the vault which reduces the post-flight time (Takei, 1991). The reduction in post-flight time means less time to produce the rotations needed to complete the vault.

A significant difference in post-flight time was reported in this study, between national (0.781s ± 0.04) and international (0.871s ± 0.03) level gymnasts, with international level gymnasts demonstrating longer post-flight times. These results were also found by Takei (1991), where there was a significant difference for post-flight time between high (0.950s) and low (0.850s) scoring vaults at the Olympic games, and Takei and Kim (1990), also found a significant difference between Olympic gymnasts (0.900s) and American gymnasts (0.830s) for post-flight time. However, Dunn, Takei, and Blucker (2007) found no significant difference for post-flight time between high and low scoring male Roche vaults.

4.6 Limitations and Future Research

Comparing temporal and spatial biomechanical variables and differences between national and international level gymnasts in the present study to other published research posed some challenges. Firstly, majority of the research was completed prior to the change in vaulting equipment from the horse to the table. Secondly, research has focused on men's vaults rather than women's. This is the first study to include gymnasts that have accolades of international and Olympic competition.

The present study has provided an up to date insight on biomechanical data for the Yurchenko group vault. It is possible to further the understanding of the Yurchenko vault, by using specific Yurchenko vaults with either a full, one and a half or double twist in the post-flight phase; however gymnast's competing these vaults at an elite level is limited. Future research needs to provide an up to date insight for Handspring or Tsukahara group vaults. The current study only focused on women vaults; future research could compare the difference between men and women's biomechanical data for the same vault type. However, men and women do not often perform the same vault within competition. Furthermore, research could focus on using the execution score provided by judges rather than the total judges' score to correlate to the biomechanical variables.

Although the current study included a larger sample size than majority research, it is still essential to work with a larger sample size of elite level gymnasts under competition conditions. Due to the nature of competition and potential judging standards, capturing data at numerous elite competitions allows for a bigger range of error within judges' score. It is necessary to capture data at a World or European Championships, to reduce the judging differences and capture vaults from the best gymnasts at that competition. When capturing at competitions it would be useful to use three-dimensional analysis where possible as vaulting involves complex rotations. However using two-dimensional analysis has fewer restrictions during a competition setting and is therefore more suitable (Prassas et al., 2006).

The International Gymnastics Federation (FIG) is the national governing body for world-wide gymnastics and informs the CoP (Fédération Internationale de Gymnastique, 2013b). Due to the rules and guidelines imposed on all competitions by the FIG, the current study did not use markers to identify individual joint centres for manual digitisation. Markers are deemed as invasive and if placed on the gymnast it could change the kinematics of the vault.

4.7 Conclusion

In conclusion, two out of 31 variables arising from the deterministic model showed a significant relationship to judges' score. The two variables were also significantly different between national and international level gymnasts. A further three variables were found to have significant differences between national and international level gymnasts. The following conclusions have been drawn: Firstly, in order to achieve a high scoring Yurchenko vault it is necessary to; 1) minimise the body angle at vault touchdown, which requires a hyper-flexed shoulder angle at vault touchdown, which is deemed important in executing the correct blocking technique to convert the horizontal velocity to a larger vertical velocity at vault take-off successfully, and 2) maximise post-flight time in order to achieve adequate height of post-flight, to ensure sufficient time to complete rotations and to prepare for a controlled landing. Secondly, significant differences between national and international level gymnasts were as follows; 1) international level gymnasts exhibited a significantly shorter pre-flight time and smaller body angle at vault touchdown and 2) national level gymnasts demonstrated a significantly smaller shoulder angle at vault touchdown, lower vertical velocity at vault take-off and shorter post-flight time.

Focusing on international level gymnasts it is evident that the main focus was to; (a) minimise pre-flight time by hyper-extending the shoulders quickly and reaching backwards, (b) minimise the body angle at vault touchdown to maximise the shoulder angle at vault touchdown to emphasise the correct blocking technique, (c) emphasise on the correct blocking technique, it allows for a larger vertical velocity at vault take-off and maximises post-flight time for international level gymnasts.

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Appendix A. Phase definitions

The definitions of the phases used, are as follows; approach phase will be defined as the last step prior to springboard contact using the first frame of contact with the floor to the last frame before take-off from the floor, springboard and vault contact phases will be the first frame where the gymnast contacts the springboard or vault to the first frame the gymnast lost contact, pre-flight and post-flight will be the first frame when the gymnast is airborne after springboard or vault contact to the first frame the gymnast contacted the vault or landing mat in accordance with Takei et al. (2003).

Appendix B. Vault entry groups

Table 6: Vault entry groups adapted from Fédération Internationale de Gymnastique (2013a, 2013b)

	Men	*Women*
1	Forward Handspring and Yamashita style vaults	Vault without salto
2	Handspring with ¼ or ½ turn in first flight (Tsukahara)	Forward Handspring
3	Round-off entry also ¼ turn, backward second flight phase	Handspring with ¼ or ½ turn (Tsukahara) where gymnasts performs a twist before table impact
4	Round-off entry with ½ turn in first flight phase and forward second flight phase	Round-off entry (Yurchenko) backward entry on table
5	Round-off entry with ¾ or 1/1 turn in first flight and backward second flight	Round-off with ½ turn in 1st flight phase, forward entry on table

Appendix C. Example Informed Consent

British Gymnastics
More than a sport

Name:

I hereby give consent to British Gymnastics to capture video recordings of myself on 6th December 2014 at Glasgow World Cup C II to be used by British Gymnastics tv and future research conducted by British Gymnastics.

I also consent for the video footage to be used for marketing and publicity related purposes, and I understand that the footage and research may be published on British Gymnastics website or elsewhere.

I understand that:

- My footage will be held in the accordance with the Data Protection Act;
- My footage could be on British Gymnastics tv or used within future research;
- I can ask British Gymnastics to stop using my video footage as part of research at any time, in which case the footage and data collected will not be used in any future publications but may continue to appear in publications already processed.

I therefore give my consent to;

- Be recorded and broadcasted by British Gymnastics tv.
- Allow the footage to be used for promotion of gymnastics and future research.
- Allow the footage to be published on British Gymnastics website or elsewhere.

Signed…………………………………………………………

Date……………………………………………………………

Print Name……………………………………………………

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British Gymnastics is the trading name of The British Amateur Gymnastics Association
Gymnastics Enterprises Limited, Registration No 2646569, VAT Registration No 594059506
Company limited by Guarantee Registration No 1630001
Place of Registration England. VAT Registration No 100166672

Name:

I hereby give consent to British Gymnastics to capture video recordings of myself on 27th–29th March 2015 at Artistic Gymnastics British Championships 2015 to be used by British Gymnastics tv and future research conducted by British Gymnastics.

I also consent for the video footage to be used for marketing and publicity related purposes, and I understand that the footage and research may be published on British Gymnastics website or elsewhere.

I understand that:

- My footage will be held in the accordance with the Data Protection Act;
- My footage could be on British Gymnastics tv or used within future research;
- I can ask British Gymnastics to stop using my video footage as part of research at any time, in which case the footage and data collected will not be used in any future publications but may continue to appear in publications already processed.

I therefore give my consent to;

- Be recorded and broadcasted by British Gymnastics tv.
- Allow the footage to be used for promotion of gymnastics and future research.
- Allow the footage to be published on British Gymnastics website or elsewhere.

Signed…………………………………………………………

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Appendix D. Ethical Approval

Faculty of Life Sciences
Research Ethics Committee

frec@chester.ac.uk

09/06/2015

Lorna Eden
36 Fisher Avenue
Orford

Dear Lorna

Study title: **Biomechanical Indicators of the Gymnastic Vault**
FREC reference: **1025/15/LE/SES**
Version number: **1**

Thank you for sending your application to the Faculty of Life Sciences Research Ethics Committee for review.

I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation.

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application Form	1	March 2015
Appendix 1 – List of References	1	March 2015
Appendix 2 – Summary CV for Lead Researcher	1	March 2015
Appendix 3 – claire Bridgman's CV	1	March 2015
Appendix 4 – Participant Information Sheet [PIS]	1	March 2015
Appendix 5 – Written confirmation that participants have agreed for their data to be used for the purpose outlined in this proposal.	1	March 2015
Response to FREC request for further information or clarification		March 2015

Please note that this approval is given in accordance with the requirements of English law only. For research taking place wholly or partly within other jurisdictions (including Wales, Scotland and Northern Ireland), you should seek further advice from the Committee Chair / Secretary or the Research and Knowledge Transfer Office and may need additional approval from the appropriate agencies in the country (or countries) in which the research will take place.

With the Committee's best wishes for the success of this project.

Approval letter 2014-15

Yours sincerely,

Dr. Stephen Fallows
Chair, Faculty Research Ethics Committee

Enclosures: Standard conditions of approval.

Cc. Supervisor/FREC Representative

Approval letter 2014-15

Appendix E. Variable Definitions

Table 7: Definitions of variables at critical vault phases

Variable	Phases	Definition
Time (s)	SBD Contact	First frame of SBD contact to last frame of SBD contact
	Pre-flight	First frame when gymnast lost contact with SBD to last frame before VT touchdown
	VT Contact	First frame of VT contact to last frame of VT contact
	Post flight	First frame when gymnast lost contact with VT to last frame before landing
Distance (m)	Round-off Distance	Last foot contact prior to round-off to touchdown on SBD
	Foot TD on SBD	Distance between toes at SBD touchdown and the back of SBD
	Between SBD and VT	Distance between back of SBD and front of VT
	Hand TD on VT	Distance between fingertips at VT touchdown and the back of VT
	Between VT and landing	Distance between back of VT to touchdown at landing
Horizontal Velocity (m/s)	Approach	
	SBD TD	
	SBD TO	
	Change on SBD	The rate and direction of CoM parallel to the ground
	VT TD	
	VT TO	
	Change on VT	
Vertical Velocity (m/s)	SBD TD	
	SBD TO	The rate and direction of CoM that moves upwards at an angle of 90° to the ground
	Change on BD	

	VT TD	
	VT TO	
	Change on VT	
Body Angle (°)	SBD TD	Angle between CoM and the horizontal passing through the toes at SBD touchdown
	SBD TO	Angle between CoM and the horizontal passing through the toes at SBD take-off
	VT TD	Angle between CoM and the horizontal passing through the fingers at VT touchdown
	VT TD	Angle between CoM and the horizontal passing through the fingers at VT take-off
Shoulder Angle (°)		The average of left and right shoulder angle was used
	SBD TD	Angle between the horizontal line passing arm and mid-trunk at SBD touchdown
	SBD TO	Angle between the horizontal line passing arm and mid-trunk at SBD take-off
	VT TD	Angle between the horizontal line passing arm and mid-trunk at VT touchdown
	VT TO	Angle between the horizontal line passing arm and mid-trunk at VT take-off

SBD Springboard; VT Vault; TD Touchdown; TO Take-off.